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20 ABSTRACT (Continue on reverse side if necessary and identify by block number) An investigation of the collateral damage produced by tactical nuclear weapons was conducted under Defense Nuclear Agency Contract No. DNA 001-76-C-0039. The analysis of civilian casualties produced by prompt weapon effects (i.e., initial nuclear radiation, direct and indirect airblast effects and thermal radiation effects) was emphasized during that effort. During the early stages of that contract, an effort was devoted to identifying potential casualty-producing mechanisms which might extend		

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to ranges farther than the prompt effects mentioned above. Fires produced by thermal radiation was one of the mechanisms identified.

An effort was initiated in August of 1976 to scope the impact on collateral damage of fires produced by tactical nuclear weapons and the relationship between fires in residential areas and the resulting casualties. The effort included primary fires (those started by the thermal pulse), secondary fires (those started by secondary effects such as airblast, debris, etc.) and spread fires.

This report summarizes the results of this effort, which was primarily conducted at the Stanford Research Institute by Stanley B. Martin and Steven J. Wiersma. It should be recognized that this was a preliminary scoping effort, intended more to identify any needs for further research than to provide definitive results for a wide range of burst scenarios.

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1. INTRODUCTION

1.1 BACKGROUND

The importance of fires, initiated by tactical nuclear weapons, as a casualty-producing mechanism has been examined in a small scoping effort conducted primarily by the Stanford Research Institute. This study was intended to provide some initial guidance about the importance of this mechanism, relative to other casualty-producing effects (e.g., airblast and initial radiation), using the methodology developed under Contract DNA001-76-C-0039 to describe the effects of uncertainties in non-scenario-specific variables, i.e., those for which it is presently either impossible or impractical to treat other than as distributed variables but where enough is known about the probable range of the variables to estimate a distribution function.

Among damage assessment problems, fire effects are exceedingly complex, requiring the treatment of a remarkably large variety of weapon-burst, environment, and target parameters. This complexity, which has often caused the problem of fires following nuclear attack to be either ignored or treated in an inadequate, over-simplistic fashion, can now be handled in a more satisfactory way as a result of research efforts funded by DCPA (and its predecessor agency, OCD). It is still necessary, however, to attempt to generalize the analysis, substituting class-average statistics and stochasticism for details and determinism, and to invent plausible algorithms where data do not exist.

The general approach being used here is to scale fire initiation data from the DCPA "Five-Cities Study" (for example, see Ref. 1), which were for weapon yields in the megaton range, to weapon yields in the range 0.1-10.0 KT and heights of burst from 200 to 600 ft/KT^{1/3}. These data are then used to compute probabilities of fire initiation and spread and subsequent casualty production caused by people caught in the burned-out region, e.g., because they are non-ambulatory due to injuries from other weapon effects, blocked by debris, overcome by smoke and toxic combustion gases, and so forth. As discussed in Appendix A, some comparisons have also been made with Japanese experience.

1.2 STUDY OBJECTIVES

This initial study has the principal objective of ascertaining the overall degree of improvement in predictions of casualties (produced by all weapon effects) that could be achieved from more detailed, yet practical (in both attainment and application), knowledge in the following areas.

1. Basic physical phenomena such as the several poorly understood blast-fire interactions that may extinguish or delay the development of primary fires, secondary (blast/shock induced) fire initiations, fire development and spread mechanisms, spread of wildland fires into populated areas, and the effects of weather conditions.
2. Target descriptions such as different types of European structures and their spacings, contents, and wildland surroundings.
3. Operational factors such as the amelioratory effects of civil preparedness (e.g., covered windows) and fire-fighting efforts.

4. More detailed treatments of the casualty-producing mechanisms associated with fires, in particular the sequence of events that may impact movement and rescue, including their dynamic features in relation to the changing fire threat.

The remainder of this report contains a discussion of the approach now being used to model the physical aspects (initiation, development and spread) of fires. Example calculations are then given for two low-yield airbursts near a residential area, and the extent of the burned-out region is compared with that of other potential casualty-producing effects.

2. PRIMARY AND SECONDARY FIRES

2.1 FIRE PREDICTIONS FOR LOW-YIELD WEAPONS

Fires in structures following a nuclear detonation are postulated to be the result of fires produced by three separate mechanisms:

1. Primary fires - those initiated by the thermal pulse of the bomb.
2. Secondary fires - those initiated by the blast effects of the bomb.
3. Spread fires - those resulting from subsequent propagation of both primary and secondary fires.

The primary fire threat to an urban target arises mainly from the initially small, incipient fires that result from the exposure of building contents by that portion of the direct thermal radiation from the nuclear fireball that is transmitted into rooms through windows and open doors. In many circumstances, exterior ignitions would play only a minor role. Normally, the exceptions would be the relatively infrequent cases where large accumulations of combustible litter or wild-land fuels are in close proximity to structures having wooden exteriors. It must be recognized, however, that structural damage resulting from any previous weapon effects (either nuclear or conventional) and the associated debris they may create will generally enhance the importance of exterior ignitions and increase the incendiary vulnerability of the urban target. In conducting this preliminary scoping study, we have chosen to neglect the contribution of exterior ignitions. The

results may therefore tend to underestimate the fire problem. However, other assumptions may compensate for this neglect; and the unavoidably large uncertainties in the total analysis will certainly mask it.

Secondary fires - those caused by blast effects rather than by the thermal radiation - require the coexistence (at the time of blastwave arrival) of fuels and energy sources in suitable combinations that mechanical damage or displacement can bring about contact between the two that is favorable for ignition of the fuels. This requirement represents an inherently low, but not insignificant, likelihood for secondary fire starts in most urban occupancies experiencing blast overpressures capable of causing the requisite damage or displacement.

Whether a fire starts from primary or secondary causes, it has the propensity to grow and to spread to other structures that escaped initial fire starts. In time, this spreading of fire from structure to structure can cause much more damage than that represented by the initial fires alone. Because they take time to develop and since their outcome is subject to alteration by subsequent events, these spread fires impact survival and the conduct of emergency operations in several importantly different ways than initial fires do; and in detailed predictions for specific cases it is important to know their distributions in time (their dynamics) as well as in space. In this study, however, spread dynamics are not treated explicitly; and the additional (ultimate) contribution made by spread fires is evaluated.

To estimate the distribution of primary fire starts, this study makes use of a methodology that was originally proposed by John and Passel⁽²⁾ and subsequently developed into an analytical procedure at URS⁽³⁾ to estimate the frequency-spatial distribution of initial structural fires in a given urban use (or occupancy) class.

2.1.1 Basic Assumptions

The analytical methodology is built upon a foundation of the following postulates and assumptions:

1. The primary fire threat arises from ignition of room contents. We have already noted that under "normal" circumstances exterior fires will contribute relatively little to the total urban fire problem. An additional justification for the neglect of exterior fires is to be found in the large thermal radiation exposures needed to ignite (to sustained burning) sound wood of thicknesses typically used for wall sheathing, roof covering, external trim, and other exterior structural purposes. (A description of ignition thresholds is discussed later.)
2. Inside buildings, ignition of lightweight kindlings is not a sufficient condition for a sustained, building-threatening fire. Either a major fuel item - one that by itself is capable of flashing over the room in which it is located - must be ignited directly, requiring a higher exposure, typically, than that required to ignite kindlings, or one or more of the ignited kindlings must provide an indirect (or independent) route to the same endpoint.
3. The contributory roles of kindlings and major furnishings may be mathematically combined as a set of conditional probabilities for each of the separate fuel classes. These classes are then chosen in such a way as to minimize the number of quantifying properties that will require evaluation; e.g., class-average ignition thresholds and probabilities of (a) exposure, (b) ignition-given-exposure and (c) flashover-production-given-ignition.
4. The room contents are randomly distributed, at a uniform height above the floor, over the plan area of the room.
5. The frequency distributions of fuels (room contents) in each class, in each occupancy, etc., are well approximated by the Poisson statistic.

2.1.2 Model Description

In its simplest form, the methodology may be represented by the equation:

$$P_r = 1 - \exp[- \sum_i (\mu p_e p_f)_i]$$

This equation predicts the probability, P_r , that a room (on a given floor, in a building of specified occupancy) whose windows are exposed to the thermal radiation from the fireball will suffer a fire that, if left unattended, will ultimately cause the room to become engulfed in fire (e.g., to "flashover"). The symbol i designates the separate classes of fuels into which the room contents have been classified. For convenience of analysis these classes will usually be chosen to discriminate between (1) those contents which each individually have the capability, once ignited, to flashover the room containing them ($i = +1$); (2) those lesser contents that, singly, lack the capability but may, if ignited, contribute to the development of a flashover situation ($i = -1$); and, to include as a separate and exclusive category, (3) those contents which are used to cover windows for privacy and the control of light ($i = 0$). The three essential fuel-class properties are μ , the mean number of ignitable items in the class per room; p_e , the probability of thermal exposure; and p_f , the probability that ignition will lead to flashover. These properties are separately expressible as functions of the radiant exposure variable, Q .*

* In fact, however, neither p_e nor p_f are explicitly given as functions of Q . John and Passel proposed a correlation between p_f and Q that we might consider using. We do use the basic form of their empiric p_e (?), and 0 correlates with Q .

The analytical convenience afforded by the foregoing classification of room contents is readily seen in the following development. For the class $i = +1$, p_f , by definition, equals one. Similarly, by definition, p_e is practically close to unity for the class $i = 0$. Thus, the basic equation may be satisfactorily approximated by:

$$p_r \approx 1 - \exp \left\{ - [(\mu p_e)_{+1} + (\mu p_e p_f)_{-1} + (\mu p_f)_{0}] \right\}$$

Now, the probability of exposure of any randomly selected point in the exposure plane (the horizontal plane within the room over which the contents, aside from window coverings, are assumed to be randomly distributed) may be related to the elevation angle θ (measured in radians) of the fireball line of sight by means of the following empirical expression:

$$p_e \propto \theta^{1.7} e^{-4.7\theta}$$

Intuitively, one expects this probability to increase in proportion to the fraction of the exposed wall area that is represented by unobstructed window area; and, consistent with results of the Five-City Study, the foregoing equation may be modified accordingly:

$$p_e = 3 \frac{A_{\text{window}}}{A_{\text{wall}}} \theta^{1.7} e^{-4.7\theta}$$

We have chosen to equate p_e with the class $i = -1$ type fuels since most of its items will be of small cross section approximating points in the exposure plane. By extension, then, the

probability of exposure of the $i = +1$ class contents will be proportionately larger in relation to their generally much larger cross section. Thus,

$$p_{e,+1} = (A_{+1}/A_{-1}) p_{e,-1} .$$

In evaluating these exposure probabilities, we have chosen the distribution of $(A_{\text{window}}/A_{\text{wall}})$ values developed by IITRI from Five-City Study survey data (see Figure 1) and developed an approximate frequency distribution for (A_{+1}/A_{-1}) values from representative cross section data reported in Ref. 4.

In evaluating the fuel-class properties, the major uncertainties are the probabilities of producing room flashover given ignition of the minor-contents items, $p_{f,-1}$ and $p_{f,0}$. We have chosen to represent these by an identical log-normal distribution with its mean located at 0.01, to indicate the relatively much smaller capability such contents have of producing a flashover situation, and their 95% confidence limits set at 0.0002 and 0.5 to reflect our almost total ignorance of this fact

In view of the foregoing, the basic equation may be simplified as follows:

$$p_r = 1 - \exp \left\{ - \left[\frac{\mu_{+1} A_{+1}}{A_{-1}} + p_f (\mu_{-1} + \mu_0) \right] p_{e,-1} \right\} .$$

Only the mean number distributions of ignitable fuels in each class remain to be evaluated.

These mean-number distributions may be expressed generally as the following nondimensional functions of the radiant

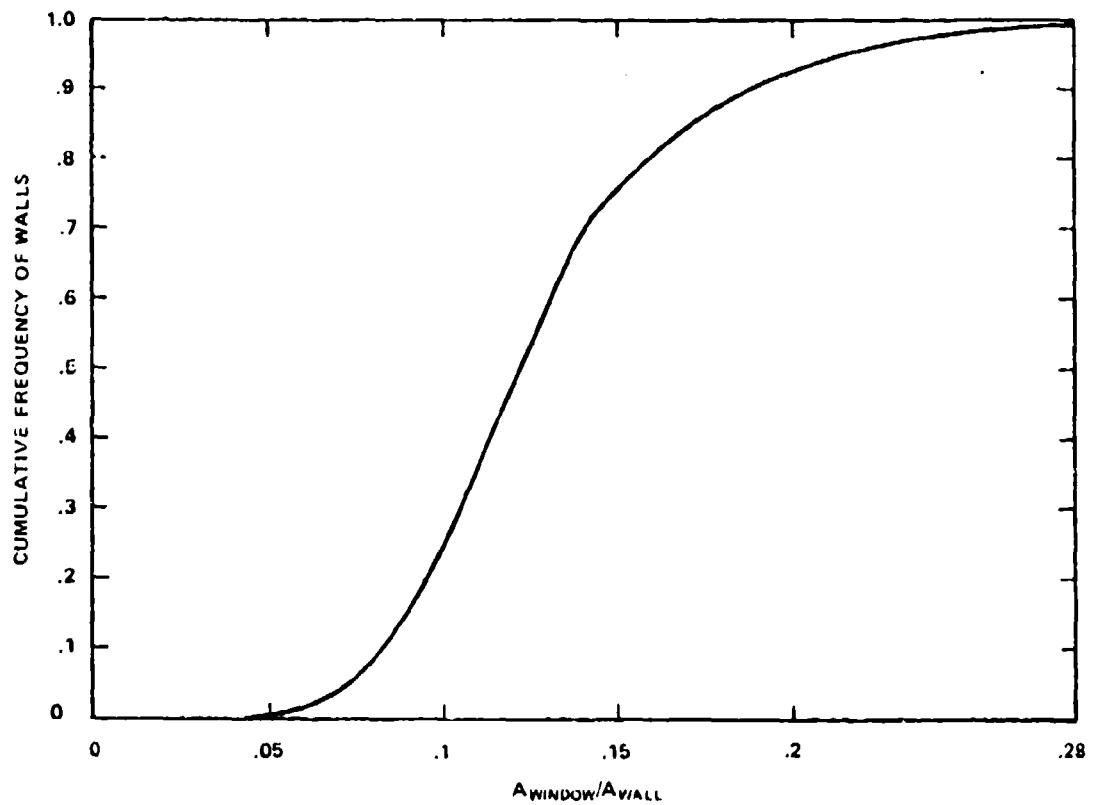


Figure 1. Frequency distribution for window areas. This is an average of survey data from San Jose, Detroit and Albuquerque.

exposure Q :

$$\frac{u_i(Q)}{M_i} = \left[1 + \frac{B+1}{B-1} \left(\frac{Q}{Q_{infl,i}} \right)^{-B} \right]^{-1},$$

where M_i represents the total count (mean number per room) of items in the i th class, and, therefore, its value depends only on the class and the occupancy (that is, it is completely independent of the weapon yield, burst height, etc.). The quantity Q_{infl} is the value of radiant exposure corresponding to the inflection point in the mean-number function. Although it will vary systematically with fuel class and occupancy, it is also a function of the conditions of burst and is the parameter used to extrapolate from one weapon burst situation to another. The quantity B is a measure of the spread in ignition threshold values for the items comprising the class. The slope of the distribution function at the inflection point is equal to $(B^2 - 1)/4B$.

The mean-number coefficients used in the present analysis are derived by an extrapolative procedure from survey data acquired during the Five-City Study. The Five-City Study dealt with megaton-yield explosions; therefore, the reference Q_{infl} values must be scaled down over some three orders of magnitude in energy yield from the megaton range to yields of interest in the kiloton range. Scaled heights of burst were of comparable magnitude except that the Five-City Study included some surface bursts.

For the scaling of Q_{infl} we have used these equations:

$$Q_0 = 2250 \frac{\rho c L}{a} \tau + \frac{t_{max}}{a}, \quad \tau < 0.52$$

$$Q_0 = 1522 \frac{\rho c L}{a} \tau^{0.4} + \frac{t_{\max}}{a}, \quad \tau \geq 0.52,$$

where $\tau = \sqrt{\alpha t_{\max}} / L$, the Fourier modulus, is a heat conduction property of the exposed fuel. The symbol t_{\max} represents the time delay (in seconds) from the instant of explosion to the appearance of the principle thermal irradiance maximum at any distant target location. For purposes of these calculations (in which all burst heights are less than 15,000 feet), t_{\max} is related to explosive yield in the following way:

$$t_{\max} = 0.0417 W^{0.44},$$

where W is the yield measured in kilotons.

It is estimated that the dependence of Q_{infl} on humidity is

$$Q_{\text{infl}} = Q_{0,\text{infl}} (1 + 0.005 h),$$

where h is the relative humidity in percent.

The practical ranges of the pertinent material properties are given in Table 1.

Figure 2 illustrates the extrapolation procedure. It is important to note that the assumption has been made that transient ignition thresholds as exhibited by idealized (uniform, apertured exposures of small specimens) laboratory tests are more representative of fire initiating conditions in realistic situations than are the laboratory-determined thresholds of sustained ignition. This assumption has very little physical

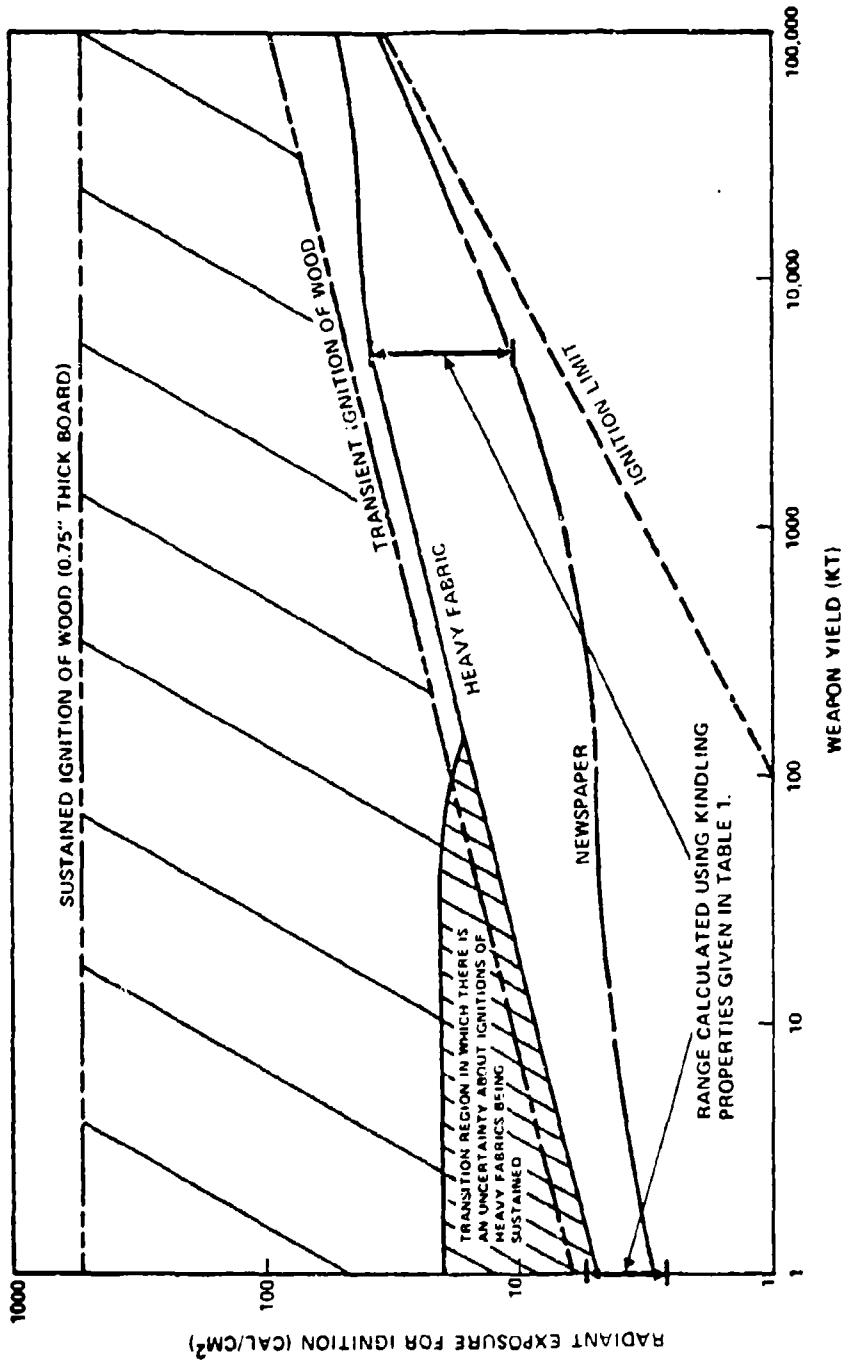


Figure 2. Radiant exposures to ignite materials (at 40-50% relative humidity) as a function of weapon yield.

Table 1. Applicable properties of ignitable room contents

Thicknesses:

$$L = 0.02 \text{ to } 0.07 \text{ cm}$$

Density of Kindling Material:

$$\rho = 0.4 \text{ to } 0.5 \text{ g cm}^{-3}$$

Thermal Diffusivity:

$$\alpha = 0.95 \times 10^{-3} \text{ to } 1.0 \times 10^{-3} \text{ cm}^2 \text{ sec}^{-1}$$

Specific heat capacity:

$$c = 0.3 \text{ cal (}^{\circ}\text{C)}^{-1} \text{ g}^{-1}$$

Absorptivity:

$$a = 0.5 \text{ to } 0.8 \text{ (nondimensional)}$$

Critical Irradiance:

$$H_c = 0.4 \text{ cal cm}^{-2} \text{ sec}^{-1}$$

evidence to support it at the present time. The validity of this assumption will be seen to be of crucial importance to the outcome of the analysis.

Figure 3 shows the functional dependence of (μ_i/M_i) on (Q/Q_{infl}) for two values of B . In the Five-City Study, B -values for residential occupancies were nearly constant for all conditions and classes, averaging about five. Since B is a measure of the range in ignition thresholds, and for the short pulses of the kiloton range the spread is noticeably less than in the megaton range, it is appropriate to use a larger value of B in the kiloton region.

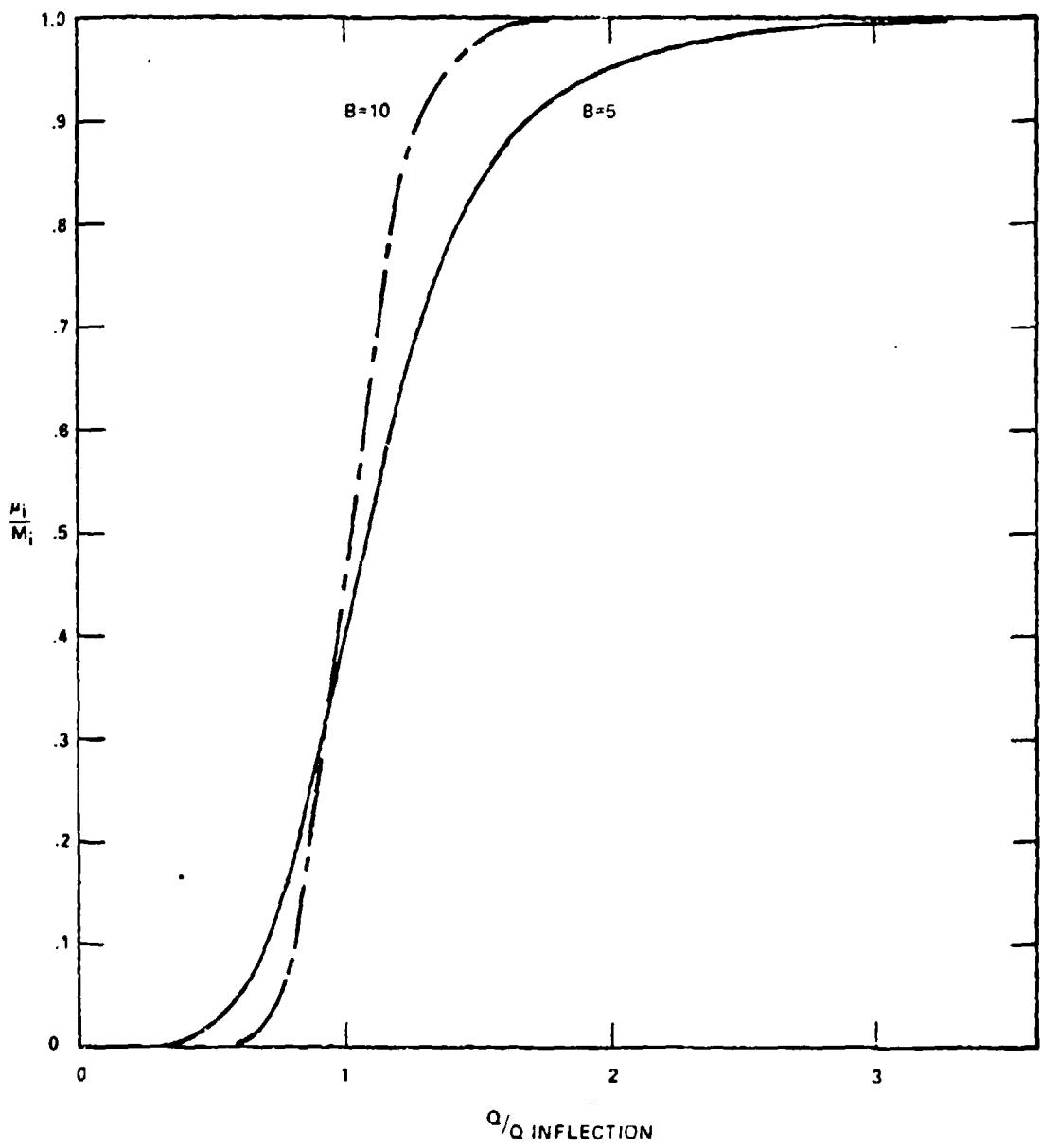


Figure 3. Mean number distributions.

It is important to note that, in the calculation of probabilities of room fires, the level of exposure Q used for determining μ_i is not the free-field radiant exposure but rather is the radiant exposure of the kindling fuel in the room, which differs from the free-field level by a proportionally constant $\bar{\alpha}$ which depends upon a number of factors and is not of uniform value for all rooms in any given building:

$$\bar{\alpha} = \bar{\alpha}_1 \cdot \bar{\alpha}_2 \cdot \bar{\alpha}_3 ,$$

where

$\bar{\alpha}_1$ = T_w , the window transmission,

$\bar{\alpha}_2$ = the fraction of the fireball not obscured by the general artificial horizon,

$\bar{\alpha}_3$ = the fraction of the fireball not obscured by local objects (i.e., trees, nearby buildings).

The window transmission is treated as a two-level discrete distribution, namely 2/3 of the cases are assumed to have a transmission of 80% (averaged over the pertinent angles of incidence), corresponding to a single pane of glass, and 1/3 are assumed to transmit only 70%, corresponding to two panes. The transmission values are adopted from recommendations (based on actual data) given in a 1966 Naval Applied Science Laboratory Technical Report.⁽⁵⁾

Window screens would further attenuate the transmitted radiation where they are used (NASL recommended a value of 50% transmittance⁽⁵⁾ for a single pane of glass combined with screen); but, noting the apparent infrequency with which insect screens are used in central Europe, we have chosen to neglect this. The

choice of 1/3 double-pane windows and 2/3 single-pane windows is purely an arbitrary one. Better statistical information could be readily obtained.

From the fraction of the fireball obscured by the artificial horizon, curves of the general form illustrated in Fig. 4 can be constructed. However, the artificial horizon should be treated as a scenario-dependent variable. Observations (including inclinometer measurements) made both here and in Germany give some indication of the general range of values of the artificial horizon. In U.S. cities, observations made from windows in one- and two-story buildings indicate a fairly consistent angle of inclination in the range 5° to 6° . In suburban areas and open country with nominal free coverage, such as one typically observes around the villages of Central Europe, the angle will average about 3° and rarely exceed 5° or fall below 2° . The principal exception is in heavily forested and mountainous areas such as the Black Forest where the artificial horizon (though it is often hard to define exactly) will range from about 10° to 15° and, surprisingly, even in the deepest canyons will rarely exceed 20° .

We have used a lognormal distribution of the artificial horizon with a mean of 3° and 95% confidence limits of 1.5° and 6° .

The fraction of the fireball obscured by "local" objects is currently prescribed by the summer/winter distribution derived from the San Jose survey as a part of the Five-City Study and shown here in Figure 5. Obviously, this is another scenario-dependent variable.

Once the separate probabilities of significant room fires have been estimated with the distributed variables given using

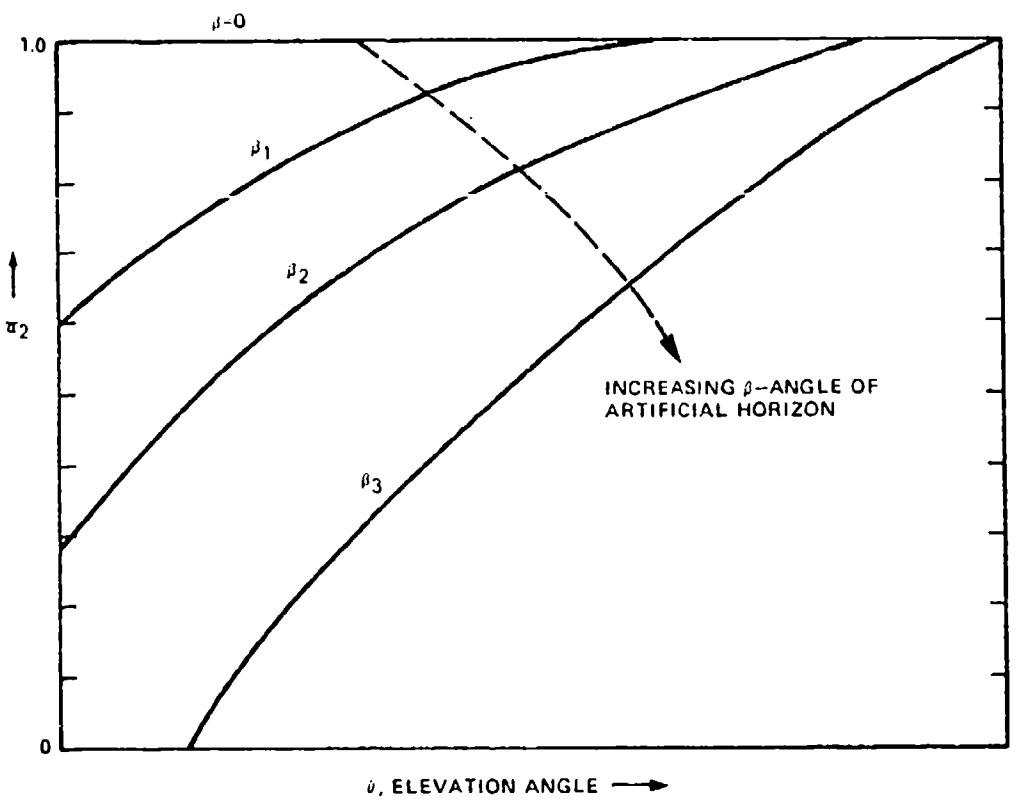


Figure 4. Trend of fireball obscuration vs. angle of artificial horizon.

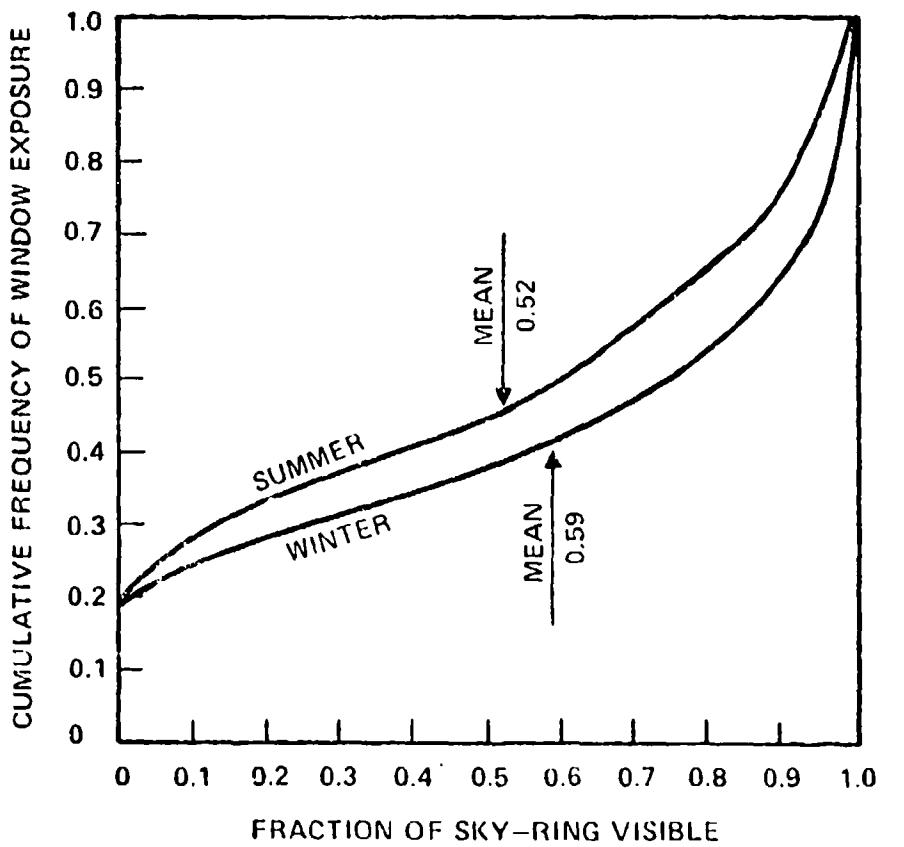


Figure 5. Exposure of first-story windows in San Jose residential area in summer and winter (based on survey of 300 windows).

the methods just described, these are then combined as

$$P_b = 1 - [1 - P_{r(1)}][1 - P_{r(2)}][1 - P_{r(3)}] \cdots [1 - P_{r(N)}]$$

to provide an estimate of the probability of significant (that is, self-sustaining and potentially life-threatening) fires in the exposed population of buildings (denoted P_b). The index $j = 1, 2, 3, \dots, N$ designates the component exposed rooms contained by the structures in question. The number N should be determined (as a distributed variable) from a survey of West German villages. In the Five-City Study the mean value for single-family residences was found to be close to 5. It might be expected to increase somewhat linearly in proportion to the number of family units in a residential structure. We have chosen to use three separate "flat" distributions of equal likelihood over the arbitrarily assumed range of values. The ranges are 4 to 8 exposed rooms in single-family residences, 6 to 12 in two-family residences, and 10 to 30 in larger, multiunit apartment houses.

Once we have estimated the function $P_b(Q)$ we can readily calculate the ultimate burnout given (1) the number of buildings H_1 in a half-block (e.g., rows of 2 to 10 structures assumed to have an equal frequency of occurrence) and (2) the side-to-side fire-spread probability P_s . The empirical equations derived for this purpose are as follows:

$$\text{Fraction burned out} = \frac{P_b}{A + BP_b}$$

in which

$$A = 1 - 1.21(H_r - 1)^{0.096} P_s + 0.538(H_r - 1)^{0.038} P_s^2$$

and

$$B = 1 - A.$$

An example, taken from a URS study⁽³⁾ for a row of 5 structures, is shown in Figure 6. Single structures from which no spread is possible must also be accounted for. For single structures the fraction of ultimate burnout equals the probability of initial ignition.

Survey data are needed for these estimates; but for initial estimates we have used side-to-side spread probabilities based on the San Jose data from the Five-City Study.

A preliminary estimate of the number of buildings in rows was made for purposes of the scoping study from aerial photographs of villages in the Niedersachsen Region of West Germany. Tallies were made of the frequency of observation of single (isolated) buildings and rows of 2, 3, 4 ... up to and including 10 or more. Although there were variations in the sums, no particular trends were found and we therefore decided to use a flat distribution (equal likelihood of occurrence of an isolated structure or any one row "length" up to and including the case of rows having 10 and more buildings). The terms "row" and "isolated building" are difficult to define precisely, but in practice the meaning is clear and unambiguous. Cases of isolated buildings have been included in the distribution function because, although they make no contribution to the fire spread, they are a part of the population pool and must be accounted for in the burnout estimate.

The probability-of-spread distribution (only side-to-side, that is, along-the-row, spread events have been included) was derived from the statistical data of the Five-City Study (San Jose residential areas) illustrated in Figure 7, making use of a physically plausible relationship between probabilities of

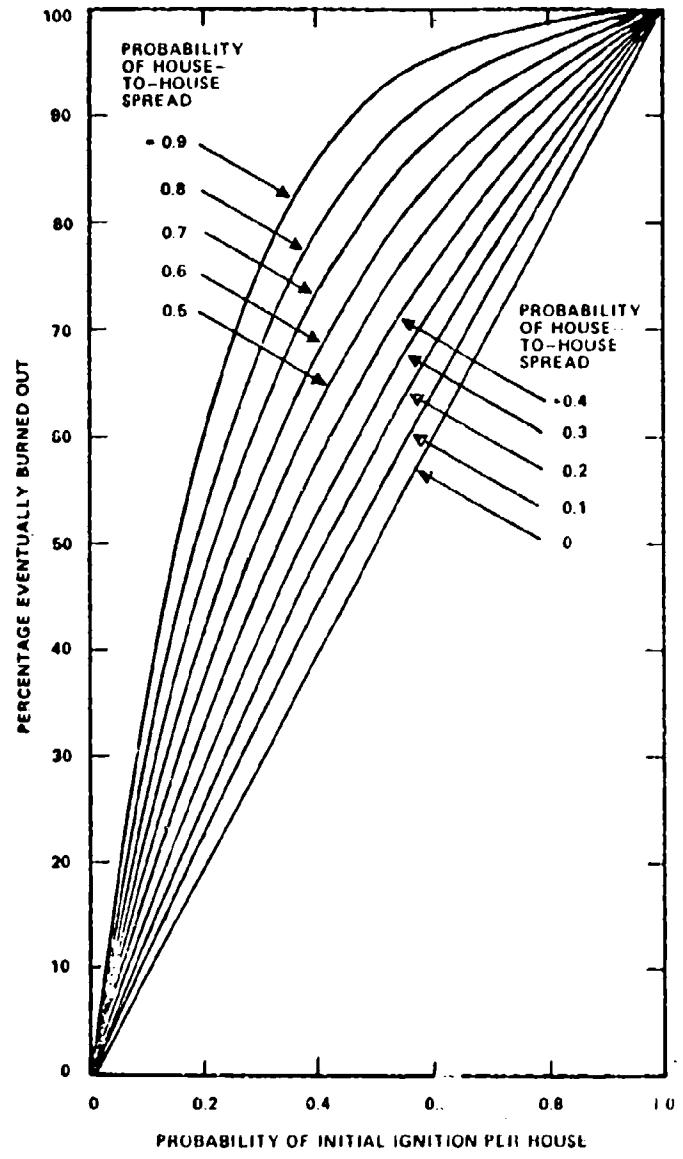


Figure 6. Average total burn for an isolated row of five houses.

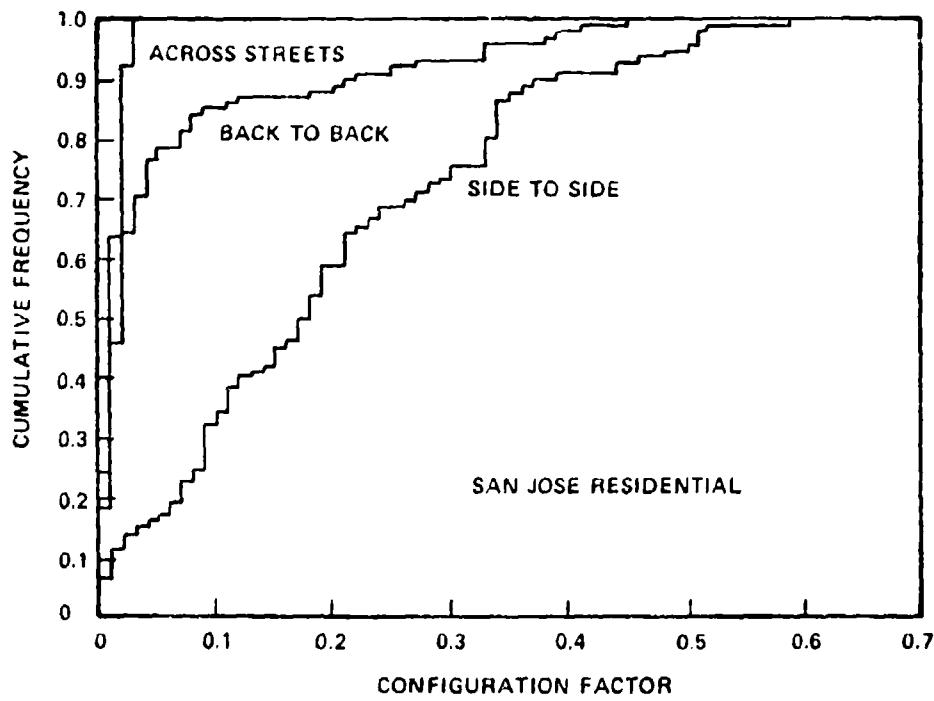


Figure 7. Distribution of configuration factors in San Jose residential areas.

fire spread and configuration factors utilized in the calculation of radiation intensities from burning (fully involved) buildings. (See Figure 8.) Inasmuch as critical irradiances for spontaneous ignition of materials are in the range of about 0.2 to 0.6 cal cm^{-2} sec^{-1} , averaging about 0.4, while windows of rooms filled with flame radiate in the neighborhood of 4 cal cm^{-2} sec^{-1} , depending upon fuel loading, ventilation, and other factors, fire spread by radiation heating alone can be expected to occur in a large proportion of the cases when configuration factors (calculated for the burning building as "seen" by the as-yet-unignited building) exceed about $\phi = \frac{0.4}{4} = 0.1$. Thus, we expect the probability of spread to rise abruptly in the vicinity of $\phi = 0.1$ from small values that are representative of spread by spotting and piloting mechanisms (no more than a few-percent probable at distances where ϕ falls to 0.05 and below) to probabilities approaching unity at $\phi = 0.2$. This function is shown in Figure 8. Combining this with the side-to-side spread probability statistics from the Five-City Study, we derived the frequency distribution function for fire-spread probabilities as shown in Figure 9 and used in this study.

2.2 EFFECTS OF BLAST

All the foregoing has ignored airblast and its effects on fires, which include (1) the interaction of the blast wave with the fire and (2) secondary fire ignitions. The effects of airblast and fire are inseparable, and their interactions are of great importance to the determination of population survival. Over those direct-effect areas where fire effects are important there will typically be substantial structural damage from blast. Even at large distances from ground zero, approaching the limit of incendiary reach, the effects of airblast on fires will be considerable. In most residential

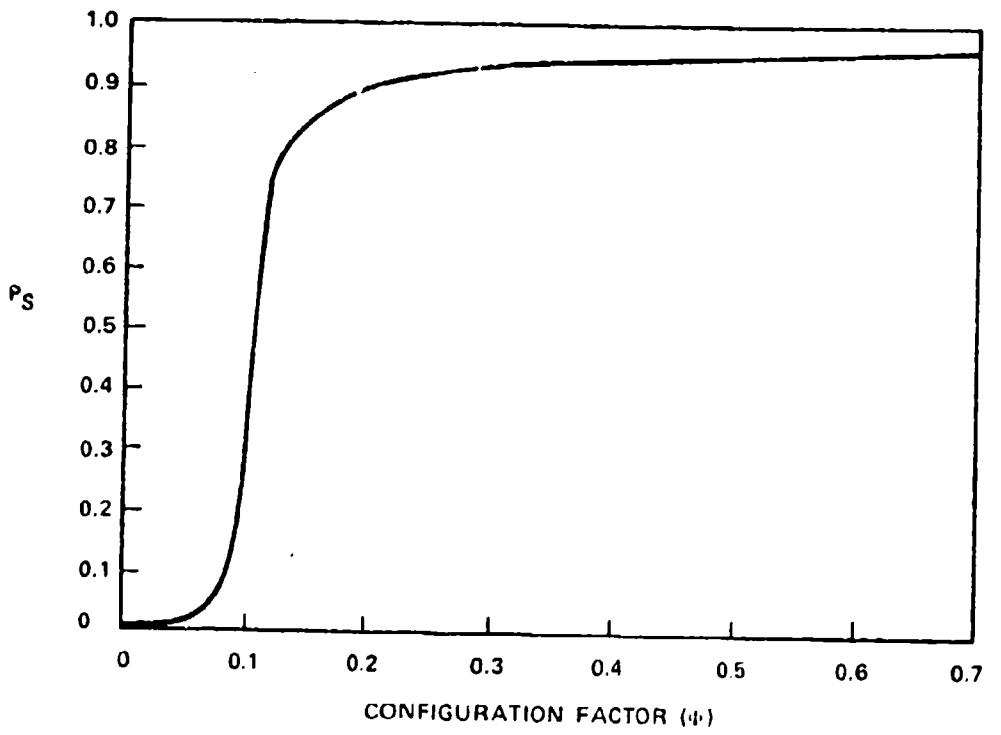


Figure 8. Probability of fire spread as a function of the configuration factor.

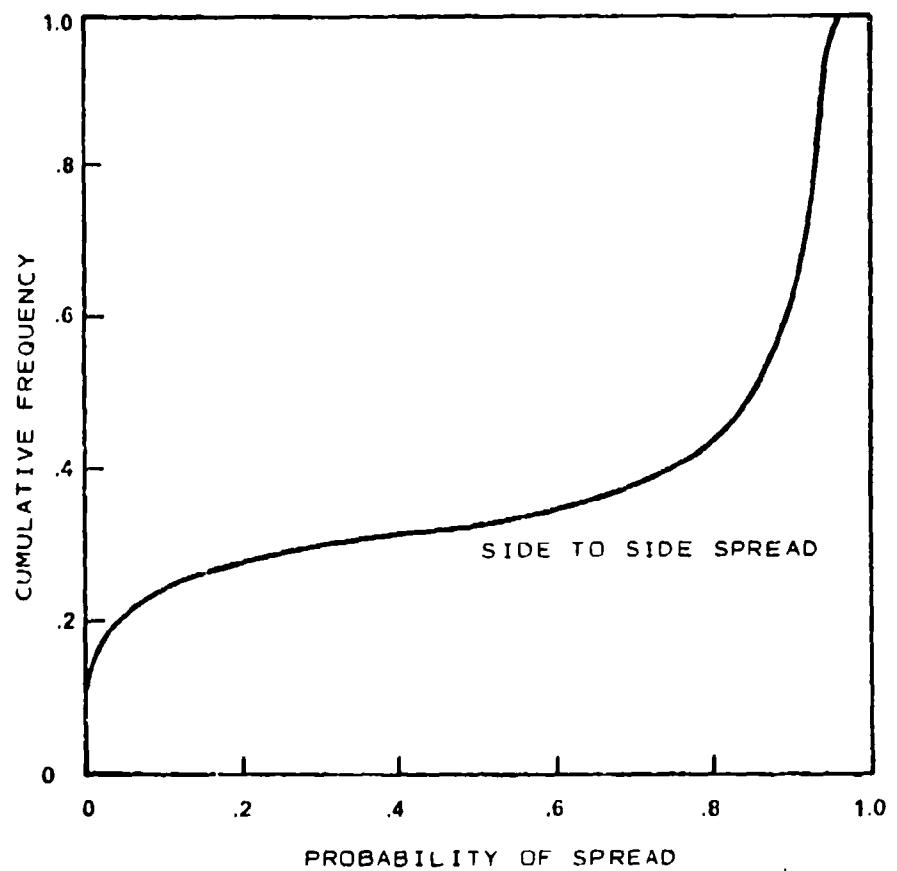


Figure 9. Probability of side to side fire spread.

areas, some structural damage, including partial collapse, accompanies fires of any practical consequence. This alters the environment in which the fires will develop and spread. Moreover many fires may be extinguished by the airblast (or at least degraded from active flaming combustion to smoldering). The same applies to commercial and industrial occupancies except that, at the limit of incendiary reach, there will be, in general, less structural damage. Nevertheless, substantial change will be wrought by blast including (1) the loss of curtain walls and interior partitions, (2) the ejection of these structural components along with contents to form debris in the open spaces between buildings, and (3) some of the actively flaming initial fires will be extinguished or reduced to a less active smoldering state.

The question of whether (and how many) fires are extinguished by the blast wave is of extreme importance to survival and the planning of emergency operations to aid survival in the immediate period following attack. It cannot, as yet, be answered confidently. Studies of the effects in Japan and at various nuclear and high-explosive tests are contradictory and leave the question unresolved. Laboratory experiments that simulate blast loading of urban interiors show that the blast wave typically does extinguish flames but often leaves the material smoldering to reinitiate active flaming at a later time. It is not certain at present how universally this behavior may extend to actual urban targets experiencing a nuclear explosion. Undoubtedly, some fires will survive the blast; others will be started by it. In all likelihood, the ultimate extent of damage will not depend nearly as heavily on whether or not blast extinguishment occurs as it will on how the blast either aids or impedes the effective application of self-help firefighting by the resident population.

While blast damage may hinder this action, the blast wave may provide some additional time by snuffing out many actively flaming fires, leaving relatively slow-growing smoldering fires in their places.

Where blast overpressures are high enough to cause substantial structural collapse and to create deep, nearly continuous debris fields over much of the local area, the spread of fire and its threat to survival could be quite different in character from that modeled in this study. Where initial fire incidence is light, fires will burn in a spotty, sporadic fashion with little or no interaction. Basement spaces and structures still standing will usually provide fire-safe refuge. With proper precautions, a very high level of survival can result. Self-help firefighting can be important in the relatively infrequent circumstances where fires do start in (or quite near to) occupied buildings. Occupants have, perhaps, 1/4 to 1/2 hour to find and extinguish these fires. Air vents to underground shelter must be freed of debris that might subsequently become involved in a slow moving debris fire. Where the density of fire starts is high, fire spread plays a role in the fire threat for only a short period of time while the fires are merging. The threat is, therefore, determined by the intensity of the mass fire and the environment it creates, notably the air temperatures, and the atmospheric concentrations of CO and CO₂.

In typical residential areas where fuel loadings of 1.5 to 3 pounds/ft² will constitute the debris field, maximum burning rates will range from 0.1 to 0.2 lb/ft²-min yielding about 2 lbs of CO per minute over each 100 sq ft of burning debris. The corresponding heat release rate will be 8×10^5 calories per minute per sq ft. This is comparable to the conditions generally ascribed to a fire storm and represents

a substantial threat to survival, requiring special precautions such as closing air vents for a period of a half hour or so. The much heavier accumulations of debris in buildup commercial and industrial areas will cause burn durations to last for hours. Prospects for continued survival in these areas are bleak.

For such areas, crisis relocation of the resident population is the preferred planning option. After-the-fact, remedial movement of the surviving sheltered population at the earliest threat of fire will be imperative.

Although we have been unable in this brief study to develop a model of fire spread for blast damaged urban areas, it is within the current state-of-the-art to do so.

Since these blast-fire interaction effects are not yet well defined, our estimates of them will necessarily have large dispersions. For nominal estimates we use an algorithm for blowout of fires that was previously used by URS, which states that below 2-psi peak overpressure no fires are blown out, above 5 psi only half of the primary ignitions survive the blast wave, and between 2 and 5 psi the survival of primary ignitions decreases linearly from 1 to 0.5.*

The only definitive study that has been conducted to date⁽⁶⁾ on secondary-ignition fires predicts that secondary ignition sources can account for 0.006 fires per 1000 ft² of floor area in areas of the target experiencing 2-psi and higher overpressures. Additional insight, both with regard to

*⁽⁷⁾ A recently published URS report supports these earlier conclusions but points out the importance of fuel location in the room relative to the blast-induced air flow pattern.

secondary fires and casualty production by primary or secondary fires, may become available from studies of other World War II fire data analyzed under DNA Contract No. DNA001-76-C-0085, "Relative Collateral Damage."

To use the McAuliffe and Moll⁽⁶⁾ predictor of secondary-fire density, we require an estimate of floor area. In this study we estimated the average floor area of single-family dwellings to be 1667 ft² which yields a secondary-ignition-source building-fire probability of 0.01. For multiple-family dwellings we estimated the floor area to be 1000 ft² times the number of units per building.

According to a Dikewood survey of fire casualties in World War II⁽⁸⁾, fire fatalities rarely exceed 4% of the population at risk unless the fire took on the extreme dimensions and the intense nature ascribed to firestorms. Based on this, the following casualty algorithm is proposed:

1. Three percent of the total population at risk, plus all of that portion of the population at risk which is either trapped or nonambulatory, will be killed by fire effects.
2. The population at risk is defined to be that fraction of the surviving population (all of those not killed by the prompt weapon effects) which is sheltered in burning buildings.

2.3 EXAMPLE CALCULATIONS OF EXTENT OF FIRE

We illustrate here simple estimates of the extent of serious fires for a single set of scenario-dependent variables and without treating the dispersion of distributed variables. Moreover, no casualty production assumptions for fires are incorporated in this example, nor is the casualty production from other weapon effects folded with these results. (Full,

all-effects casualty calculations including distributed variables to establish confidence limits are given in other reports generated under the basic contract.) As a rough indication of the potential seriousness of fires as a casualty production mechanism for low-yield weapons, however, the range of the effects of other mechanisms may be compared to the predicted extent of the burned-out region.

This example estimates the fraction of buildings burned for the following conditions:

- (1) Weapon - (a) 1 kiloton, standard fission
(b) 10 kiloton, standard fission
- (2) Height of burst - (a) 400 ft
(b) 895 ft*
- (3) Residential area with 4 rooms per building exposed to the fireball and the following obscuration factors:
2 rooms with $\bar{\alpha}_1 = 0.8$, $\bar{\alpha}_3 = 1.0$
2 rooms with $\bar{\alpha}_1 = 0.8$, $\bar{\alpha}_3 = 0.5$
- (4) Visibility of 10 miles
- (5) Artificial horizon = 3°
- (6) Total burn calculated for isolated rows of 5 houses with house-to-house spread probability of 0.67.
- (7) Windows are not covered.

The calculations were made with and without a consideration of blast effects. When considering blast effects it was assumed:

- (1) Below 2-psi peak overpressure the blast wave has no effect on fire.

*Height of burst scaled to give (at the second thermal maximum) a fireball line of sight equivalent to 1 kiloton at 400 feet.

(2) Above 2 psi peak overpressure (a) a fraction equal to the quantity $(8 - P)/6$, where P is the peak overpressure in psi, having a lower limit of 0.5, survive the blast wave blow-out to rekindle active fires and (b) an additional 1% of the buildings have secondary ignition fires.

Results of these calculations are shown in Figure 10 for the 1-KT case and in Figure 11 for the 10-KT case. With or without the blast effects, there is a significant fraction, ~10%, of the buildings completely burned out at a ground range of ~0.5 mi from the 1-KT burst and 1.2 miles from the 10-KT burst. At these ranges, and with typical protection inside residences from the initial radiation, all other weapon effects produce no significant incidence of fatalities, although the creation of debris and the incidence of non-fatal, incapacitating injuries from other effects are not insignificant at this range. For these cases, then, the possibility exists that fire could be among the dominant fatality mechanisms at long ranges.

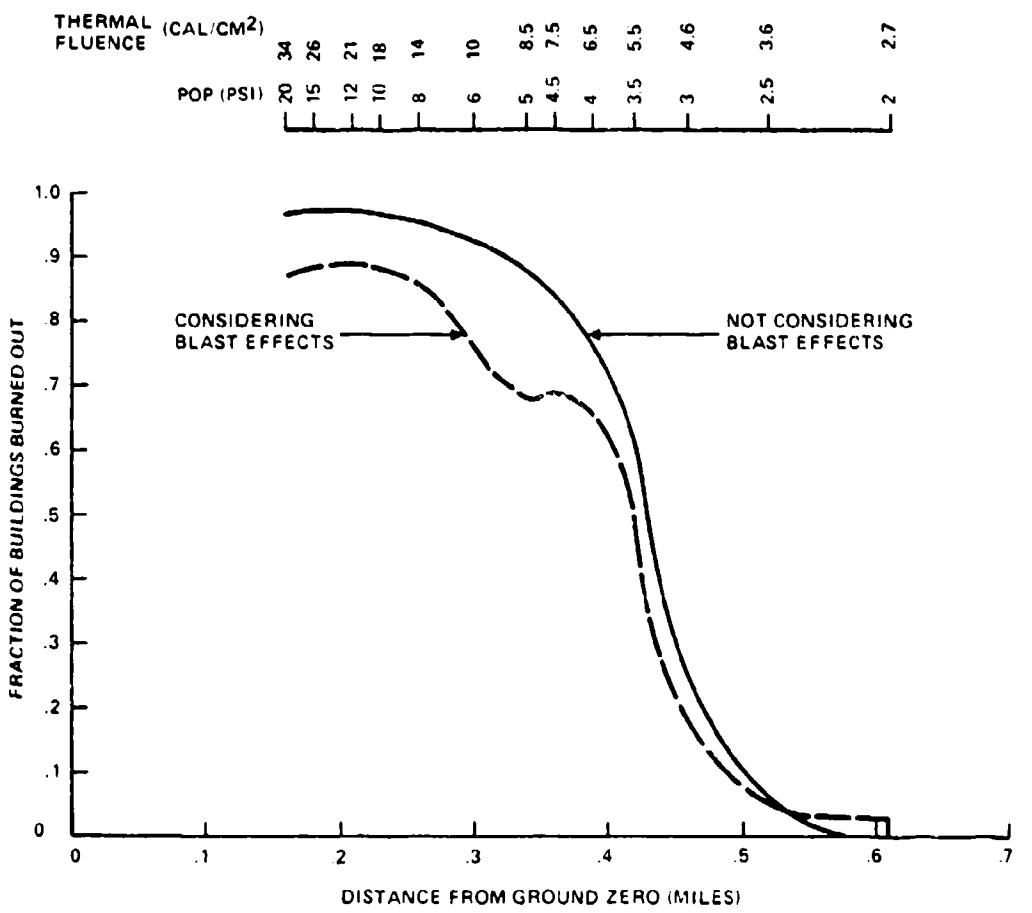


Figure 10. Fraction of buildings burned out for 1 KT weapon.

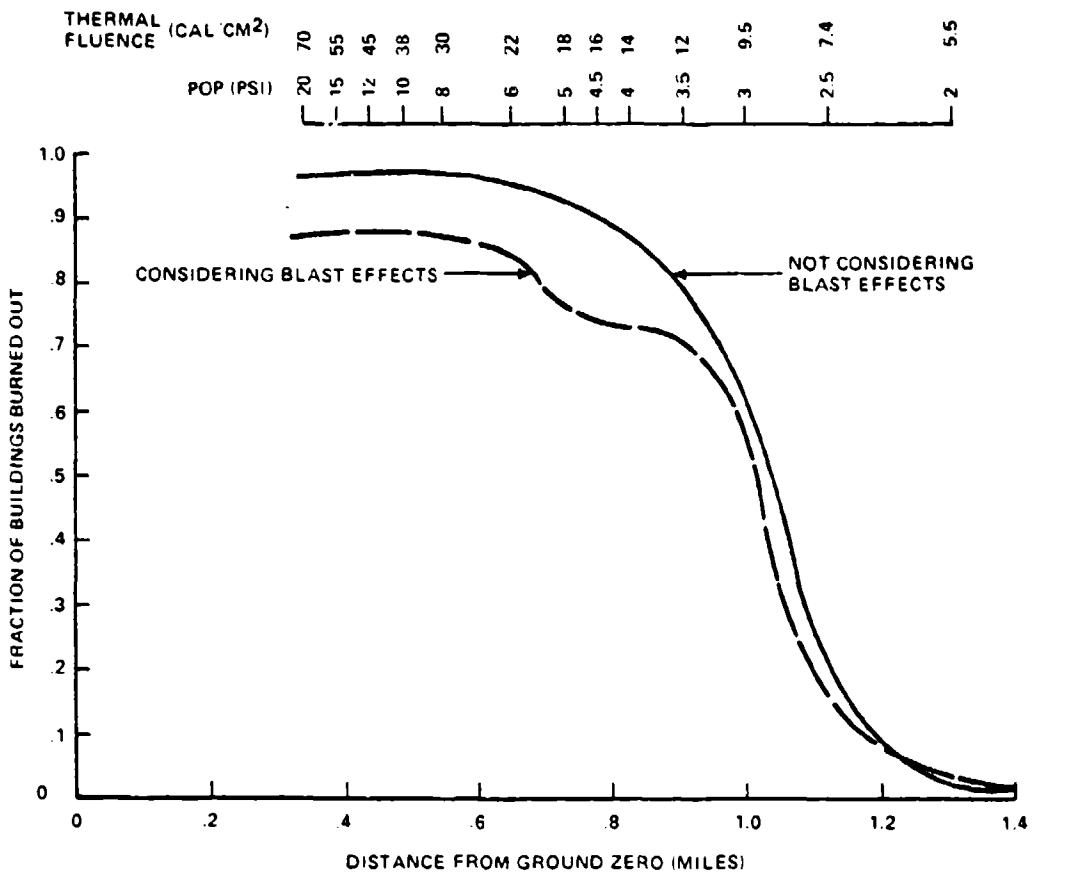


Figure 11. Fraction of buildings burned out for 10 KT weapon.

3. CONCLUSIONS AND RECOMMENDATIONS

This analysis shows that, for tactical situations involving the use of nuclear weapons in Western Europe, collateral fire effects could be quite important. It also shows how strongly dependent the fire outcome is on scenario-related variables.

These "scenario-related" variables are numerous and cannot, and should not, be treated in the same way as the physical variables that have some inherent dispersion. They include such factors as the following:

1. Burst height and yield
2. Sequence of two or more bursts
3. Warning of the population and its response to warning, e.g.,
 - a. closing shutters and boarding up windows
 - b. emergency housekeeping
 - c. movement to shelter
 - d. delegation of fire watch
 - e. preparation for self-help fire fighting
4. Indirect threat due to wildland fires.

The height of burst critically affects (i.e., becomes the principal determinant of) the extent of primary fires whenever the artificial horizon obscures a significant portion of the airburst fireball. The range of 200 to 400 ft SHOB appears to be the main transition region, provided the assumed artificial horizon for typical West German villages is reasonable.

A similar consideration applies to the probability of exposure of interior (room content) fuels. The probability is a strong function of the line-of-sight elevation angle, peaking at about 22° above the horizontal; but it is complicated by trees and buildings in the immediate vicinity of the exposed building (and considered separately from the artificial horizon). This uncertainty is decreased by information on building heights and separations appropriate to particular locales.

Moderate blast damage caused by one explosion can markedly increase the fire susceptibility of an urban target subjected to a second burst. This effect has not been considered in analyses to date. Other than its effect in removing shutters and other coverings from windows, it is not yet clear what analytical formalism would be applicable, nor what additional data might be needed.

A simple but very effective primary-fire countermeasure is the expedient covering of windows with opaque material. Simply closing a shutter can be quite effective in virtually eliminating all possibility of interior fire starts from a single explosion. This and other countermeasure options could be evaluated to provide some quantitative measure of relative effectiveness for population defense planning.

The indirect threat due to wildland fires is properly treated in terms of such scenario-related variables as weather (current and recent past), proximity of the urban area to contiguous, heavily vegetated areas (e.g., forests), and the number, sequence, kinds, and locations of both nuclear and conventional weapon explosions in the wildland areas adjacent to urban interfaces. Ordinarily, such indirect effects will

be unimportant, the threat is nonexistent. In a few circumstances, however, the potential threat should be recognized and an attempt made to evaluate it. In qualitative terms, the conditions accompanying the threat are the same as in any peacetime wildfire situation and much the same "spread/no-spread" rules will apply. The main differences will be magnitude and suddenness of threat development, and the phenomenon of crowning may occur in even the managed forest of Europe where it rarely if ever occurs under ordinary circumstances. Nevertheless, this is strictly a problem for limited localities and adds little to the overall evaluation of collateral damage.

Because of the potential for movement of both injured and uninjured people to avoid the threat of fire and the possibility of entrapment of survivors by fire, the dynamics of fire spread must be included in more comprehensive analyses. Analytical models for fire dynamics exist but were not employed in this study because of the uncertain nature of the overall fire threat (with or without movement of people) relative to the other nuclear weapon effects.

While the blast-fire interaction had no dominant effect for the cases examined, it must be recognized that the basic blast effects and their interaction with, and/or influence on, fire behavior are still highly uncertain. In addition to a general need for research in this area, the following specific issues have been identified: (1) the importance of exterior ignitions should be evaluated for situations where interior ignitions do not dominate the fire response of the target; (2) some consideration should be given to situations involving previous damage from either nuclear or conventional weapons and to how this damage could modify the conclusions regarding fire effects; (3) improved casualty algorithms should be

developed from the historical and other retrospective sources of data (e.g., data from both wartime and peacetime experiences in which fire casualties followed explosions and/or structural collapse) in combinations with mathematical modeling of the dynamics of fire spread as it may impact survival (i.e., "fire trapping"); and (4) an effort should be made to resolve through experimentation the longstanding uncertainty about which laboratory-determined ignition threshold applies (or if neither does, what then?) to practical situations involving the exposure of mixed and geometrically complex fuel arrays.

Finally, this analysis has identified particular target-description variables to which the results are most sensitive, using, as a starting point, values taken from the Five-City Study. The applicability of those values can be determined by comparison to values specific to the particular local of interest.

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APPENDIX A
INFERENCES ABOUT FIRE PREDICTION
FROM THE JAPANESE EXPERIENCE

As a check on the prediction of fires, both to improve the methodology and to enhance the credibility of the results, some analytical estimates have been made, independently of the results of the postwar bombing surveys, of the fire damage in the Hiroshima and Nagasaki attacks of World War II. After establishing the scenarios, including relating free-field Q's to peak overpressures and distances from ground zero, we have successfully forecast the gross features of the incendiary damage within the uncertainties of the bombing survey results (see Tables A-1 and A-2). Despite the obvious differences between the 1945 atomic bombings and any tactical deployments contemplated for Western Europe in the future, this seemed to be a useful exercise because it represents a large extrapolation from the "Five-City Study" in the direction of tactical yields, and it offers the only real examples of urban targets impacted by the direct effects of a nuclear explosion.

The bombing survey estimates of fire damage resulting in Hiroshima and Nagasaki are shown in Figures A-1 and A-2 as functions of distance from ground zero. Our calculated predictions of burnout are shown in the same figures for purposes of comparison. Included also are the predicted initial fires, indicating by difference the contribution made by fire spread.

A detailed analysis of the two affected areas was not conducted. We simply used average values of fire spread, building density, and structural variables for single-family residential areas as derived from the Five-City Study.

Table A-1. Hiroshima fire data

<u>Distances From GZ (ft)</u>	<u>No Fire</u>	<u>Primary Fires</u>	<u>Secondary Fires</u>	<u>Spread Fires</u>	<u>Total Fires</u>	<u>Total Buildings Surveyed</u>	<u>Fraction Burned (%)</u>
0 - 999	0	5	3	7	15	15	100
1000 - 1999	0	5	5	10	20	20	100
2000 - 2999	1	4	3	5	12	13	92
3000 - 3999	2	5	3	7	15	17	88
4000 - 4999	5	1	2	13	16	21	76
5000 - 5999	6	0	1	10	11	17	64
6000 - 6999	10	0	2	9	11	21	52
7000 - 7999	12	0	0	4	4	16	25
8000 - 8999	19	0	1	0	1	20	5
9000 -	16	0	0	0	0	16	0

Table A-2. Nagasaki fire data

Distances From GZ (ft)	No Fire	Primary Fires	Secondary Fires	Spread Fires	Total Fires	Total Buildings Surveyed	Fraction Burned (%)
1000 - 1999	7	68	7	30	105	112	94
2000 - 2999	20	30	3	15	48	68	71
3000 - 3999	26	5	6	12	23	49	51
4000 - 4999	46	1	3	5	9	55	16
5000 - 5999	33	1	6	11	18	51	35
6000 - 6999	18	0	4	9	13	31	42
7000 - 7999	2	0	0	0	0	2	0
8000 - 8999	8	3	0	8	11	19	58
9000 - 10,000	13	2	0	0	2	15	13
10,000 - 12,000	5	4	0	13	17	22	77
12,000 -	68	0	0	0	28	0	0

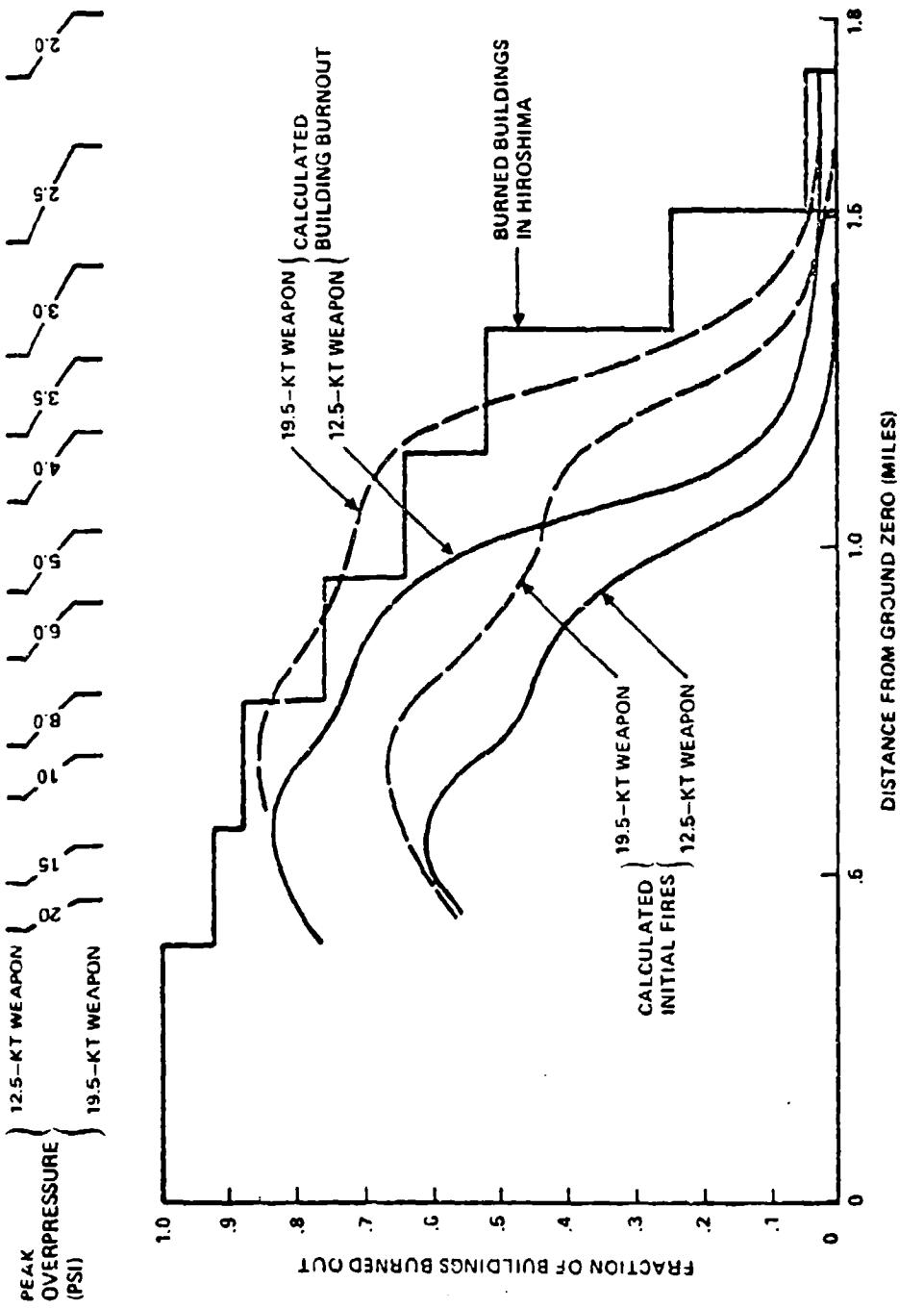


Figure A-1. The Hiroshima fire data and predictions.

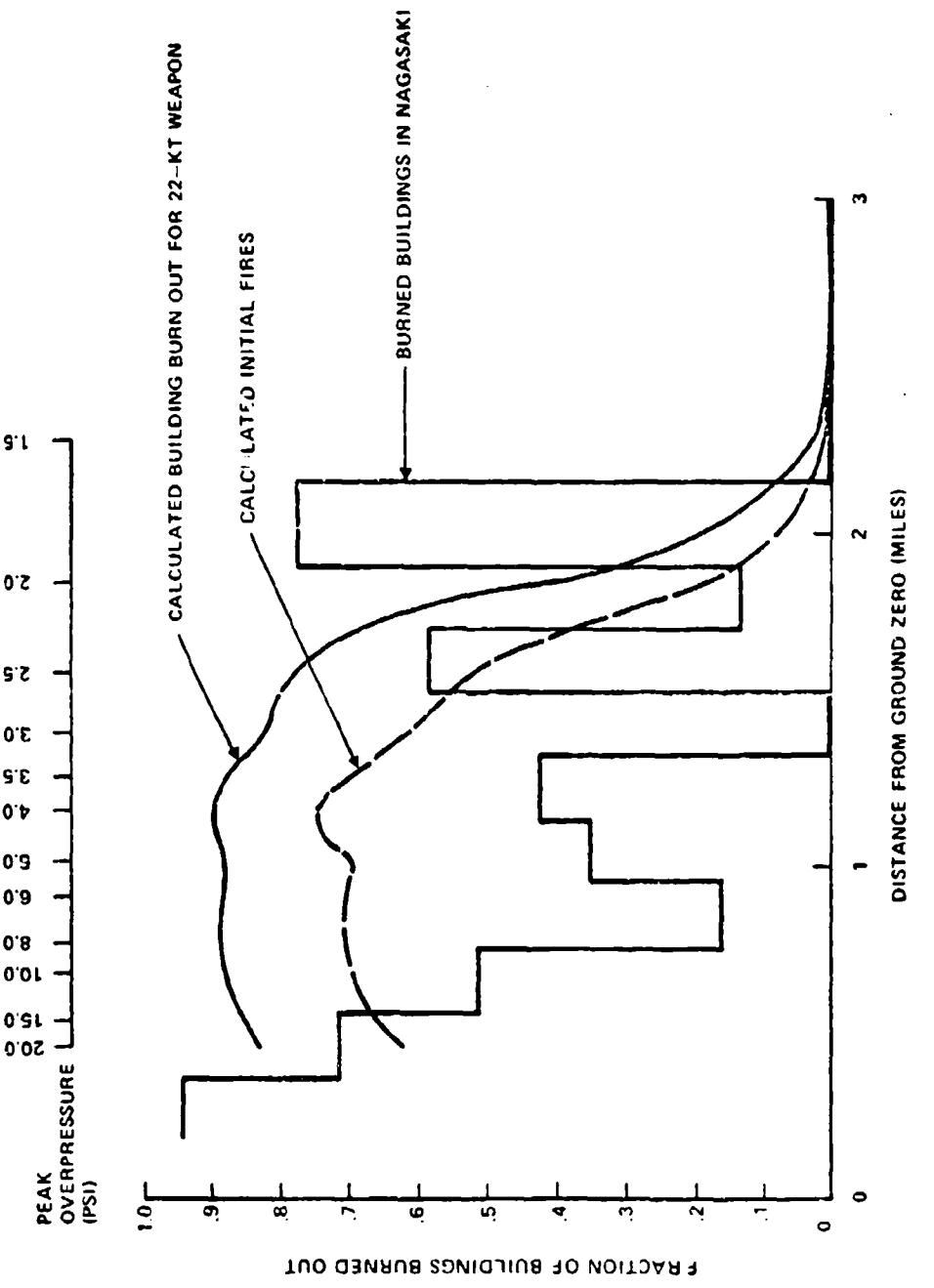


Figure A-2. The Nagasaki fire data and predictions.

For the Nagasaki case, as shown in Figure A-2, the predicted building burnout does not agree nearly as well with the fire data. It is felt that especially the characteristics of the structures, terrain effects, and other important scenario variables may have been much different than the "average residential area" variables that were used for predictions. The damaged area in Nagasaki was a heterogeneous complex of varied topography, containing a wide range of building use classes and structural types. However, it was not possible to look more closely at the area characteristics within the scope of this project.

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